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# Seasonal Coefficient of Performance of Heat Pumps

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## ABSTRACT

Energy performance of air conditioning systems has a great importance especially with the high growth of air conditioning usage contributing to high level of electricity consumption and $CO_2$ emissions. In this context, the objective of this study is to establish a seasonal performance index for heat pumps in heating mode ESCOP (European Seasonal Coefficient Of Performance) equivalent to the index developed for chillers ESEER. Therefore, this article will present a methodology to determine average operating conditions consisting of a complete study of European heat pumps market and reconstitution of building sectors heated by heat pumps. As a result, typical buildings are chosen as representative clusters and modeled in a way to simulate energy demands for these typical building in different climates. This procedure is concluded by the identification of weighted average at defined operating conditions.

## 1. INTRODUCTION

Energy performance of air conditioning systems has got a great importance especially with the high growth of air conditioning use contributing to high level of electricity consumption and $CO_2$ emissions. In fact, within a few years, HVAC systems sales moved from a random distribution to a market focused on higher efficiency offer. Thus labelling for HVAC systems is more and more mandatory worldwide. USA has been always the pioneer with the Air-conditioning and Refrigeration Institute (ARI) and the Department of Energy (DOE) by setting strict energy efficiency guidelines and rating standards for manufactures. On the other hand, Europe has Eurovent Certification certifying the performance ratings of air-conditioning and refrigeration products according to European and international standards, and other main countries have followed this market transformation case of Japan, China, Korea, etc. Uniform standards are underway for all applications of cooling and heating and will be applied by CEN and ISO by 2009.

European Seasonal Energy Efficiency Ratio ESEER similar to the US-IPLV Integrated Part Load Value is a weighted formula enabling to take into account the variation of Energy Efficiency Ratio EER of chillers with the load ratio and the variation of air or water inlet condenser temperature. In this context, the objective of this study is to establish a seasonal performance index for heat pumps in heating mode ESCOP (European Seasonal Coefficient Of Performance) equivalent to the index developed for chillers ESEER.

Therefore, this article will present a methodology to determine average operating conditions consisting of a complete study of the European heat pumps market. Next step is the reconstitution of building sectors heated by heat pumps classified by type “residential, small commercial, retail, large offices”, and by age “retrofit, new installation in existing buildings, installation in new buildings. As a result, typical buildings are chosen as representative clusters and modeled in a way to simulate energy demands for these typical building in different climates. This procedure is concluded by the identification of weighted average at defined operating conditions. Seasonal coefficient of performance will be then evaluated for different part load operations during the year in each country, and for all Europe. This work will lead to elaborate an index better estimating the real performance of heat pumps.

## 2. EUROPEAN HEAT PUMP MARKET

### 2.1 Main Figures of Heat Pumps in Europe

Heat pump market is expanding rapidly in Europe as described in Figure 1, with the development of commercial sectors especially offices and the economical growth in the South.
The European study represented below is based on the number of heat pump systems sold in European countries between 2002 and 2006 collected from a survey done with manufactures of heat pumps and reversible chillers. This number of units can be expressed by the corresponding heat pump heated floor area through this equation (1):

$$F = \frac{N \times P}{D} \quad (1)$$

where: *N* is the number of units, *P* the nominal heating capacity, *D* the heating density (W/m²) see below, and F the area heated.

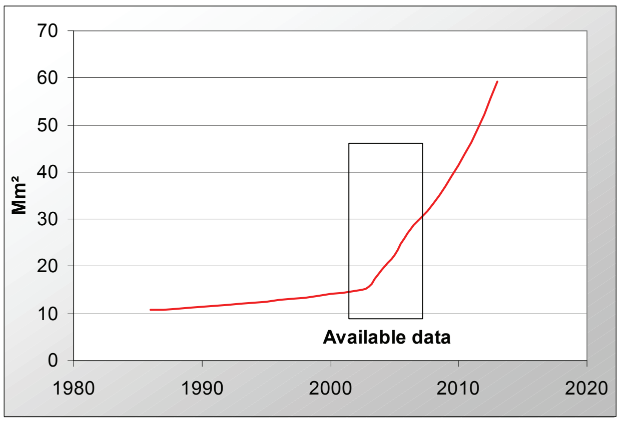


*Figure 1: Annual addition of building HP heated floor area in the EU (either really added or replaced)*

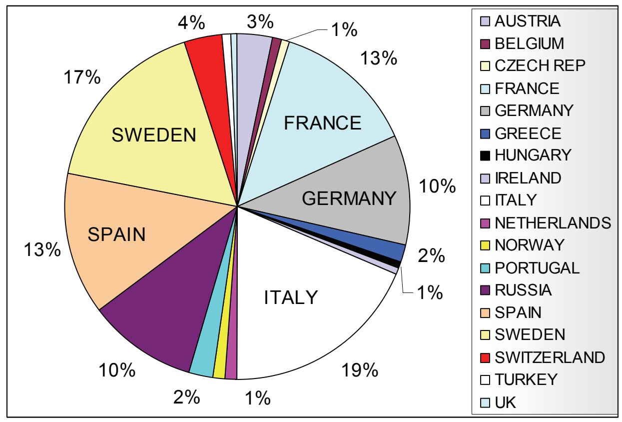


*Figure 2: National shares of installed HP heated floor area in EU countries in 2006*

The Italian market represents about 19 % of the HP heated floor areas of Europe, followed by the Swedish market 17%, the French market 13% and Spanish market 13%, where D is independent of the country.

Heat pumps accounted in this study are considered residential systems when their nominal capacity is below 17.5 kW and commercial systems when their nominal capacity is above 17.5 kW.
Heating density values *D* are issued from the sizing of the heat pump according to building type, climate, national habits, etc. For example, a heating density of 100 W/m² is attributed to a residence in Lisbon, and 140 W/m² for the same residence in Munich, while for commercial buildings heating densities are estimated to 60 W/m² in Lisbon and 75 W/m² in Munich.

The evolution of HP heated floor area in Europe between 2002 and 2006 are represented by sector, in Figure 3 for commercial buildings and in Figure 4 for residential buildings.

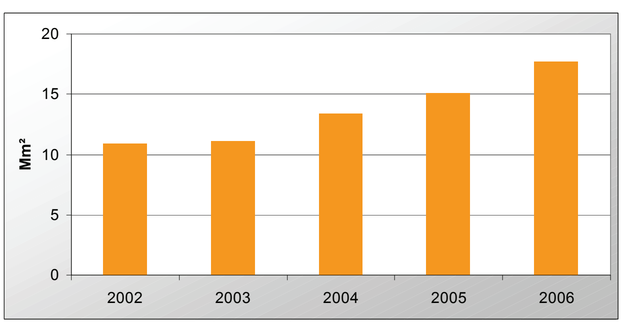


*Figure 3: Total European commercial HP heated floor area evolution between 2002 and 2006*

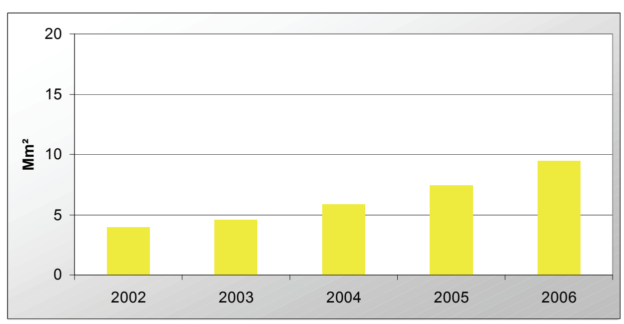


*Figure 4: Total European residential HP heated floor area evolution between 2002 and 2006*

## 2.2 Stock and Projections for 2010 and 2015

Heat pumps heated floor area (m²) stock has been estimated by integrating the number of units sold after extrapolating into the past and the future with taking the number of systems sold between 2002 and 2006 as a reference. The stock (Figure 5) is calculated on a base of 15 years supposed to be the average lifetime of an air conditioning system. For the years between 1987 and 2002:

$$S_{n-1} = S_n - \left[ \left( N_n - N_{n-16} \right) \times \frac{P}{D} \right] \tag{2}$$

where: - $S_0 = S_{2002}$ the initial stock,

- $N_n$ is the numbers of HP units sold every year n estimated by the equation:

$$N_{n-1} = \frac{N_n}{1+\tau} \tag{3}$$

for the years between 2002 and 2006:

$$S_{n+1} = S_n + \left[ \left( N_n - N_{n-15} \right) \times \frac{P}{D} \right] \tag{4}$$

where: - $S_0 = S_{2002}$ the initial stock,

- $N_n$ is the numbers of HP units sold every year n known for this period,

and for the years between 2006 and 2015:

$$S_{n+1} = S_n + \left[ \left( N_n - N_{n-15} \right) \times \frac{P}{D} \right] \tag{5}$$

where: - $S_0 = S_{2006}$ ,

- $N_n$ is estimated through this equation:

$$N_{n+1} = N_n \left( 1+\tau \right) \tag{6}$$

τ is a growth rate of air conditioned floor area, it depends from different factors especially country demographics and economy (GDP, population, growth, development, etc.). Since, the number of units is known between 2002 and 2006, τ is calculated through the compound annual growth rate formula below. In addition to this growth rate, heat pumps floor area (m²) stock described in Figure 5, takes in consideration reversibility evolution of chillers.

$$\tau = \left( \frac{N_{2006}}{N_{2002}} \right)^{\frac{1}{2006-2002}} - 1 \tag{7}$$

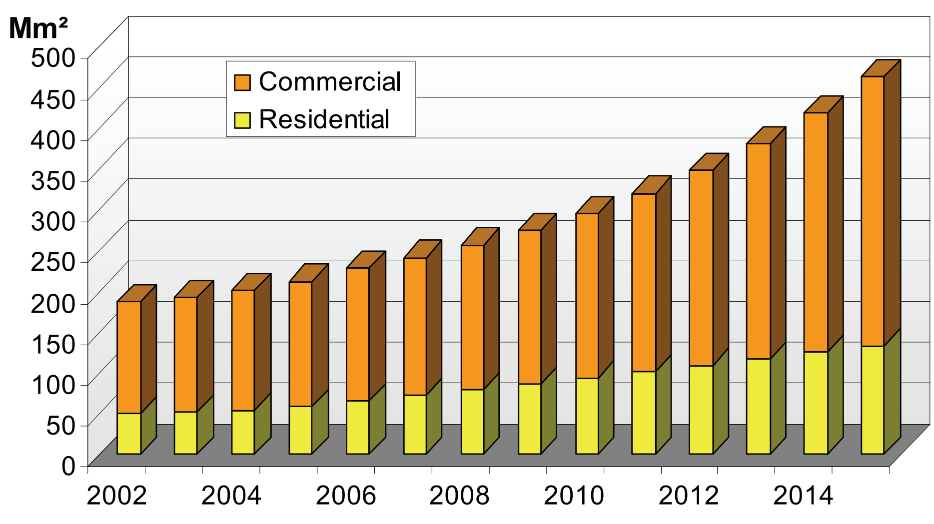


*Figure 5: Stock evolution of heat pump heated floor area by sector between 2002 and 2015 in Europe*

Total heat pump heated floor area stock is estimated to 230 Mm² for 2006 and 460 Mm² in 2015.

# 3. BUILDING SECTORS

## 3.1 Building Sectors Typology

Buildings heated by heat pumps are classified in sectors, residential, small commercial, retail, large offices, hospitals, health care institutions, hotels and restaurants, and by age retrofit, new installation in existing buildings, installation in new buildings. Heat pumps destination by building type and installation type are represented respectively in the tables 1 and 2 below based on statistical surveys on the behalf of producers and distributors:

Table 1: Heat pumps destination by building type in Europe

| Residences | Offices | Hospitals/ Health Care Institutions | Retail | Hostels/ Restaurants | Other Buildings |
|---|---|---|---|---|---|
| 35% | 20% | 7% | 7% | 13 % | 18% |

Table 2: Heat pumps destination by installation type in Europe

| | Residences | Offices | Hostels/ Restaurants |
|---|---|---|---|
| Retail/New | 25% | 75% | 20% |
| First installation in existing building (boiler replacement or non heated surface) | 70% | 20% | 80% |
| Retrofit (heat pump replacement) | 5% | 5% | 0% |
| Total | 100% | 100% | 100% |

Typical buildings are chosen as representative clusters and modeled in way to simulate energy consumption for these typical building in different climates. In particular, a 100-m² residence will represent residential buildings, and office building types will represent commercial buildings in this paper.

## 3.2 Description of Buildings

The residence (Rivière et al., 2006) is as an apartment with 100 m² floor area. Its roof and facades are exposed surfaces in four orientations, while the floor is detached to a fully symmetric zone with identical boundary conditions. The exterior dimensions are 8 by 12.5 m with a total floor area of 100 $m^2$. The vertical wall area is 98 $m^2$. Distinct windows are placed in each wall with a window to wall ratio of 0.15, where operable shades are used. The residence is modelled as two zones: a conditioned zone representing 30% of total floor area, with south and west exposed facades, and the rest is considered as an unconditioned zone.

Typology of office buildings has been chosen from a study of the French building stock (Filfli, 2006 and Stabat, 2007):

- The first type corresponds to buildings of huge areas mainly glazed. It is subdivided into three branches listed below with their estimated repartition in percentage of total office buildings:
  - 1a) Broad open space offices 14%,
  - 1b) Broad partitioned offices 20%,
  - 1c) Thin partitioned offices 33%.
- The second type concerns the buildings subjected to renovation. Its surface area is medium and this type is less glazed than the first one 8%.
- The third type concerns the small buildings existing in the industrial suburban zones 25%.

Table 3: General characteristics of the office building types

| Building type | 1a | 1b | 1c | 2 | 3 |
|---|---|---|---|---|---|
| Description | Buildings of huge areas mainly glazed | | | Renewed buildings | Small buildings of industrial suburban zones |
| | Broad open space offices | Broad partitioned offices | Thin geometry - glazed meeting room | | |
| Stock share in % of surface | 14% | 20% | 33% | 8% | 25% |
| Total surface area | 15 000 m² | | | 5 000 m² | 1 000 m² |
| Floors (including ground floor) | 12 | | | 4 | 2 |
| Height under ceiling | 3 m | | | 3 m | 2.7 m |
| **% of surface area by type of use (with respect to useful total surface area)** | | | | | |
| Offices | 78% | 55% | 60% | 55% | 58% |
| Meeting rooms | 16% | 22% | 21% | 22% | 18% |
| WC | 3% | 3% | 3% | 3% | 3% |
| Circulations | 3% | 20% | 16% | 20% | 21% |
| **% of outside walls surface area (with respect to useful total surface area)** | | | | | |
| Total | 45% | 50% | 66% | 67% | 104% |
| Vertical walls (opaque and glazed) | 37% | 42% | 58% | 42% | 54% |
| Roof | 8% | 8% | 8% | 25% | 50% |
| Glazed surfaces (vertical) | 13% | 17% | 26% | 9% | 21% |
| | 50% of vertical surfaces with window | | | 27.5% of vertical surfaces with window | 34% of vertical surfaces with window |

### 3.3 Building Energy Simulations

Simulation of the residence was approached with TRNSYS 16, a transient simulation program, while office building types has been simulated through CONSOCLIM an intern dynamic building energy simulation tool of the Center for Energy and Processes. Both allow simulating various models and their interactions. They take as inputs: envelope characteristics or thermal insulation expressed by a U-value depending on the building age and country regulations, solar gains, orientation, occupancy loads, artificial lighting, internal load of equipments, and infiltration. Set points are defined to control the temperature.

European climates are split in few climates based on a study (Stabat, 2007) of heating and cooling degree days for the heating season taken from October 1st to May 31st; these climatic zones are defined as follow:
- Zone 1: Low heating demand, high cooling demand corresponds to south of Spain, south of Italy, French, Mediterranean cost, and Greece.
- Zone 2: Low heating demand, medium cooling demand corresponds to Portugal, North and West of Spain.
- Zone 3: Medium heating demand, medium cooling demand corresponds to North of Italy, and South of France.
- Zone 4: Medium heating demand, low cooling demand corresponds to North of France, Belgium, The Netherlands, South of UK, and West of Germany.
- Zone 5: High heating demand, low cooling demand corresponds to the east of EU-15 and North East of Europe.

Detailed energy demands simulations were carried out over a whole year on an hourly basis (8760 hours) for five regions of each climate zone: Athens, Lisbon, Turin, Paris and Munich in order to have an overview of the different European climates.
In the residence considered with old building envelope, internal loads due to occupancy are fixed to 1 person/20m², which is equivalent in this case to 5 W/m². Equipments loads are taken 7 W/m², while artificial lighting is 10 W/m² with 60% assumed as convective heat and 40% radiation heat. Occupancy, equipments, and lighting have defined schedule. Infiltration rate was set to 0.6 air change per hour.

In office building types, since there is large disparity in internal building loads, a "low" load building is taken into account in the simulations, with appliances energy rate of 7.5 W/m² in offices and a lighting power of 10 W/m² in conference rooms and offices. The occupancy profiles and the loads due to persons have a large influence on heating and cooling energy demands but low differences between buildings are assumed. A North/South orientation is considered with an internal solar shading factor of 0.4 and a high ventilation rate. Set points temperatures are fixed to: 21-24°C.

# 4. RESULTS and DISCUSSION

## 4.1 Reduced Load Curve and Weighting Coefficients

All the heating load curves from building simulations have been reduced to 10 aggregated values, one point by 10% part load, expressed relatively to the surface in W/m². Thus, a typical load is associated to every part load stage. Furthermore, an energy weight is also associated by summing all the energy needs occurring in a range of 2°C of outdoor temperature. Loads of the simulated residence are shown in Figure 6 as a function of ambient temperature, while its annual energy weights expressed in kWh/m² are described in Figure 7.

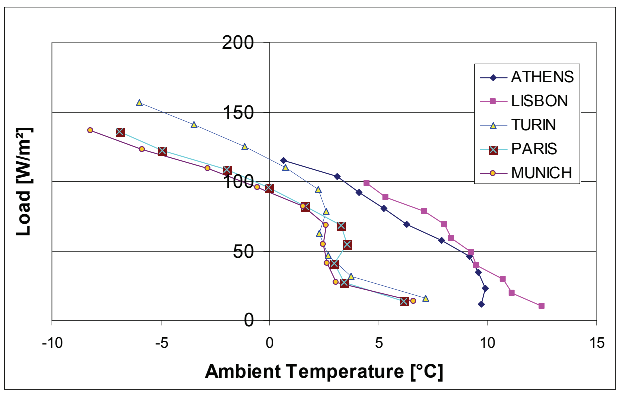


*Figure 6: Load curves in heating mode per climate of the residence*

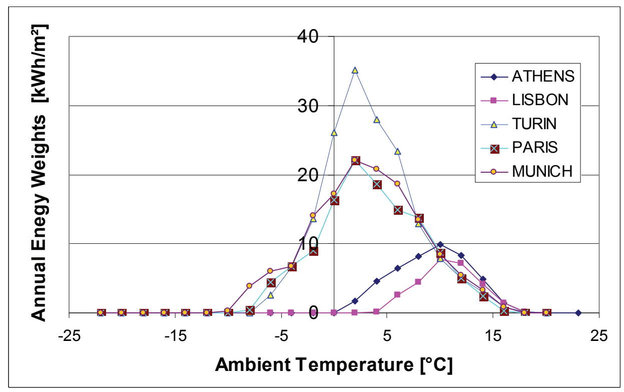


*Figure 7: Weighting curves in heating mode per climate of the residence*

Reduces load curves of office building types are presented respectively in Figure 8 and Figure 9 for only Paris climate due to space limitation.

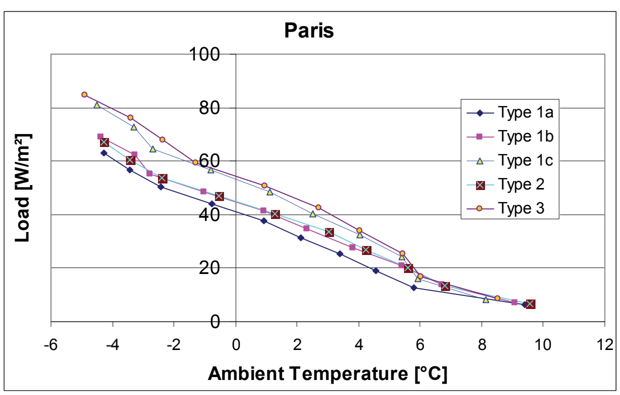


*Figure 8: Load curves in heating mode per office building type in Paris*

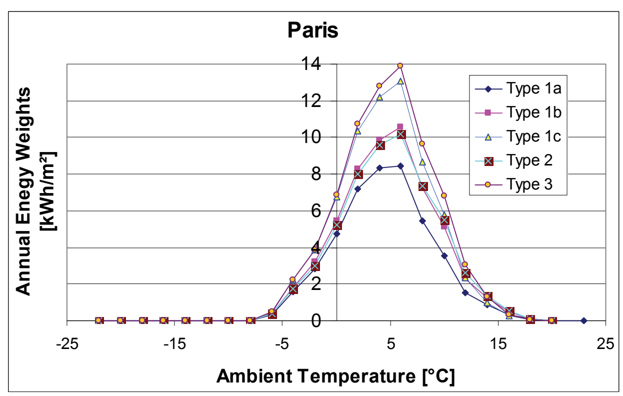


*Figure 9: Weighting curves in heating mode per office building type in Paris*

Then, the different office types results are grouped and represented as a function of the defined European climate weighted by type of office types stock share as mentioned in Table 3, for each climate i:

$$\text{Load climatic zone}\big|_i = \Sigma_{(\text{office type})} \text{Load per office type} \times \text{Share per office type} \qquad (8)$$

Figure 10 and Figure 11 show the heating demands of office building types for the 5 climatic zones:

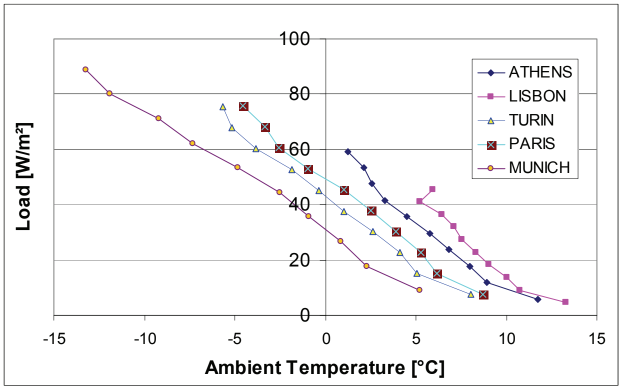


*Figure 10: Load curves in heating mode per climate of office buildings*

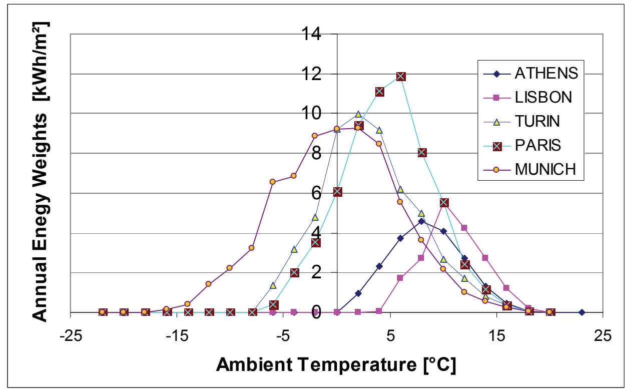


*Figure 11: Weighting curves in heating mode per climate of office buildings*

Then, these reduced curves are weighted by heat pump sales in 2006 per climatic zone, for residential and commercial sectors through the equation

$$\text{Average load building sector} = \sum_{(\text{climatic zone})} \text{Load climatic zone} \times \text{Sales share of climatic zone} \tag{9}$$

Finally, all Europe load curve for residential and commercial heating is obtained as shown in Figure 12 with its annual energy weights distributed in function of ambient temperature after weighting the average load of building sectors by their surface sector share mentioned in Table 1, 65.3% for commercial and 34.7% for residential, and by energy share (number of units) of climatic zones:

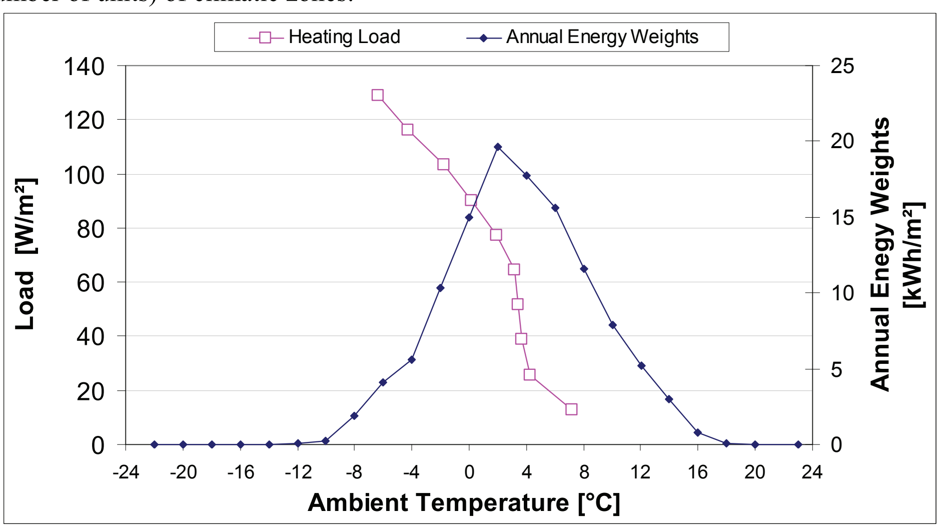


*Figure 12: Load curve and weighting curve in heating mode for all Europe with sales weights of 2006*

Therefore, European heating demands treated by heat pumps are calculated by multiplying the European annual energy weights obtained (Figure 12) by the HP heated floor area stock, they are about 27 TWh for the 230 Mm² of HP heated floor area stock in 2006 and 55 TWh for the 460 Mm² estimated stock in 2015.

SCOP index is developed by evaluating energy efficiency of heat pumps for hours when the system operates at different load rates. SCOP formula (equation 10) is based on four testing points corresponding respectively to 100%, 75%, 50%, and 25% part load rate. The weighting coefficients are calculated (A, B, C, D in equation 10) at determined testing conditions (load and outdoor temperature) for our residence, and office building types simulated for the five European climate defined previously.

$$\frac{1}{SCOP} = \frac{A}{COP_A} + \frac{B}{COP_B} + \frac{C}{COP_C} + \frac{D}{COP_D} \tag{10}$$

The harmonic mean formula adopted is preferred to the arithmetic mean used by Eurovent to assess ESEER as well as IPLV, since the electrical consumption is proportional to $\frac{1}{COP}$.

Table 4: SCOP for commercial heat pumps in Europe

| Part Load Ratio | Temperature (°C) | Weighting Coefficients |
|---|---|---|
| 100% | -6.2 | 3% |
| 75% | -3.0 | 24% |
| 50% | -0.7 | 23% |
| 25% | 6.0 | 50% |

Table 5: SCOP for commercial heat pumps for the five climates

| | Athens | | Lisbon | | Turin | | Paris | | Munich | |
|---|---|---|---|---|---|---|---|---|---|---|
| Part Load Ratio | T(°C) | Weight | T(°C) | Weight | T(°C) | Weight | T(°C) | Weight | T(°C) | Weight |
| 100% | 2.0 | 2% | 5.9 | 1% | -5.0 | 4% | -3.4 | 3% | -11.6 | 3% |
| 75% | 3.5 | 21% | 7.1 | 16% | -2.1 | 29% | -0.9 | 25% | -7.2 | 24% |
| 50% | 4.8 | 21% | 7.8 | 21% | -0.1 | 25% | 1.3 | 26% | -4.2 | 23% |
| 25% | 10.4 | 56% | 12.0 | 61% | 6.0 | 42% | 7.0 | 46% | 3.6 | 50% |

## 5. CONCLUSIONS

This work has introduced an accurate seasonal performance rating of heat pumps in Europe. The study is based on the number of units sold in European countries in the period between 2002 and 2006 by building sectors. A 100 m² residence is chosen to represent residential buildings and five types of office buildings to represent commercial buildings. Energy demands simulations were carried out for these chosen buildings for five European climates. Heating load curves obtained are reduced to 10 aggregated values associated with an energy weight function of ambient temperature.
This procedure is concluded by the identification of weighted average at defined operating conditions of part load ratio and ambient temperature. Tests will follow at standard rating conditions to validate these weighting coefficients obtained by simulations.

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TRNSYS, TRaNsient SYstem Simulation Program, http://www.trnsys.com/

## ACKNOWLEDGEMENT

This work was funded by ADEME, the French Agency for Environment Energy Management under the research project PERSAPAC.